Analysis of 31.4GHz Atmospheric Noise Temperature Measurements at Madrid Deep Space Communications Complex

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The atmospheric noise temperature at 31.4GHz was measured at NASA's Deep Space Communications Complex at Madrid from September 1990 to December 1996 excluding February 1991 and May 1992 using a Water Vapor Radiometer. These data are used to obtain the cumulative distribution for the atmospheric noise temperature at 30 degrees elevation for each month. Based on these data, the percentage weather and its associated atmospheric noise temperature for which maximum data return is attained is calculated for each month. It is determined that by designing the link for the optimum weather percentage for each month the link achieves 70% of the upper limit of the total data return volume. Furthermore, if the link is designed for the fixed atmospheric noise temperature of 34K for all months, the link achieves 67.8% of the upper limit of the total data return volume. In addition, if the aggregate atmospheric noise temperature is used for each month, the link achieves 69% of the upper limit of the total data volume return over the six years. Finally, these data were used to compare the data return volume of a deep space X-band link designed for 90% weather at 34m BWG station at Madrid (3.775 atmospheric noise temperature) to the data return volume of a deep space Ka-band link designed 34K atmospheric noise temperature (84% weather). It was calculated that the Ka-band link returns at least 6.56dB (4.5 times) more data than the X-band link for the same amount of radiated power and downlink modulation index.

I. Introduction

In order to evaluate the performance of a data link the total data return volume of the link must be analyzed. For a fixed bit signal to noise ratio ($\frac{E_b}{N_0}$) requirement for the link the data rate, and hence the total data volume, is inversely proportional to the system noise temperature (T_{sys})[1][2]. Several factors contribute to the T_{sys}. At Ka-band, the most important of these factors is the atmospheric noise temperature (T_{atm}). The T_{atm} at Ka-band is severely affected by the variations in the weather. Therefore, bad weather or high humidity could severely degrade the performance of the link at Ka-band.

The T_{atm} is measured at DSCC-10 (Goldstone) and DSCC-60(Madrid) using a Water Vapor Radiometer (WVR). The WVR data are very accurate (± 0.5 K for clear conditions, ± 1K for cloudy conditions) and could be used to calculate the effects of T_{atm} on the T_{sys} and, therefore, on the data volume. The data used to obtain the results in this paper were gathered at DSCC-60 for 74 months (Sept. 90 to Dec. '96 excluding Feb. '91 and May '92). Probability distributions for these measurements were obtained for each month. Based on these distributions, the maximum data return volume for each month was calculated and the Ka-band link advantage over X-band was estimated.

In the following sections, the details of this analysis are presented. In Section II the nature of the data is discussed and the process of generating the statistics for the data is presented. In Section III calculations for data return volume from the WVR measurements are explained. In Section IV the statistical results are discussed. In Section V results for Ka-band link advantage over X-band are presented. In Section VI the conclusions are presented.

II. The WVR Data

The WVR data used for this analysis were gathered from Sept. '90 to Dec. '96 excluding Feb. '91 and May '92. This data set contained measurements of the atmospheric noise temperature at 30 degrees elevation with cosmic background noise. The elevation of 30 degrees was selected in order to evaluate the link at typical tracking elevation angles. For the analysis in this paper the cosmic background noise was removed from the data. The data were gathered at the nominal rate of one measurement every thirty minutes. However, due to interference from other sources (which are assumed to be non-weather related) sometimes the data points were tagged as bad and were not used in the statistics. Finally, in the continuous tip curve mode the data was gathered more frequently (approximately one data point every four minutes).

Each data point represents T_{atm} measurements integrated over a ten-minute period except for when the WVR is operating in the continuous tip curve mode. For analysis purposes, each data point is assumed to be representative of ten minutes of time except for when the time tag for a data point is less than ten minutes greater than the time tag for the previous data point. In this case, it is assumed that the data point represents the T_{atm} measurements integrated over the period between the two time tags. Using these assumptions, time-weighted statistics of the data for each month, of the complete data set and of the data for each month aggregated over the years were obtained.

III. Data Analysis

The first step in analyzing the data is to create a histogram (hence a probability distribution) for each of the months. The histogram is created in a time-weighted fashion, that is, the period of time for which a temperature measurement is valid is added to the value of the bin into which that measurement falls. From the histogram cumulative probability distribution for each month is calculated. In addition aggregate histograms and distributions for each month and for the complete data set were generated.

After the histogram is obtained for each time period the maximum data volume return is calculated. It is assumed that the system noise temperature is T_{atm} plus equipment (amplifier plus antenna) noise temperature and the cosmic background noise. For this analysis, the equipment noise temperature plus the cosmic background noise is assumed to be 25K. Also for normalization purposes it was assumed that the total data volume at 1K T_{sys} and zero atmospheric loss is 100. Therefore for any atmospheric noise temperature, T_{atm} the maximum data volume possible is given by:

$$V_d(T_{atm}) = \frac{100 \cdot L(T_{atm})}{25 + T_{atm}} \qquad (1)$$

where $L(T_{atm})$ is the atmospheric loss factor at T_{atm} and is approximated by [3]:

$$L(T_{atm}) \approx \frac{275 - T_{atm}}{275} \qquad (2).$$

Given these assumptions, there are several measures that are useful for evaluating the data volume return for each month. The first of these is the "genie" data volume. The "genie" data volume assumes that perfect prediction of the atmospheric noise temperature is possible and that the data rate on the spacecraft could be instantaneously adjusted so that the received signal to noise ratio (SNR) on the ground allows for an acceptable bit error rate (BER) while maintaining maximum data throughput.

To calculate the "genie" data volume for each time period let T_n be the nth T_{atm} temperature measurement for that time period and let t_n be the time duration for which this measurement is applicable. Then, the "genie" data volume is calculated according to the following:

$$V_g = \frac{\sum_n \frac{100 \cdot L(T_n) \cdot t_n}{25 + T_n}}{\sum_n t_n} \tag{3}$$

The "genie" data volume is the upper bound on the data volume that could be obtained for any given time period. However, since perfect weather prediction is not possible, the link is designed by selecting a single atmospheric noise temperature value. Let $F_{atm}(T) = \Pr\{T_{atm} \le T\}$ be the cumulative distribution function of the T_{atm} for a given period. Then for a design atmospheric noise temperature, T_d, the total data volume return is given by:

$$V_{tot}(T_d) = \frac{100 \cdot L(T_d) \cdot F_{atm}(T_d)}{25 + T_d} \tag{4}$$

The optimum design temperature, T_{opt}, is that temperature which maximizes $V_{tot}(T_d)$, in other words:

$$T_{opt} \ni V_{tot}(T_{opt}) \ge V_{tot}(T_d) \forall T_d \qquad (5).$$

The maximum data return volume is, therefore,

$$V_{\max} = V_{tot}(T_{opt}) \qquad (6).$$

Figure 1. 80% and 99% Monthly Atmospheric Noise Temperature, Madrid, Sept. 90 to Dec. 96

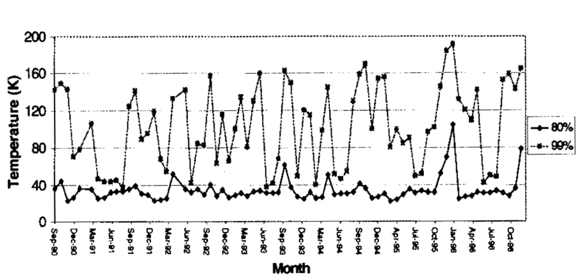
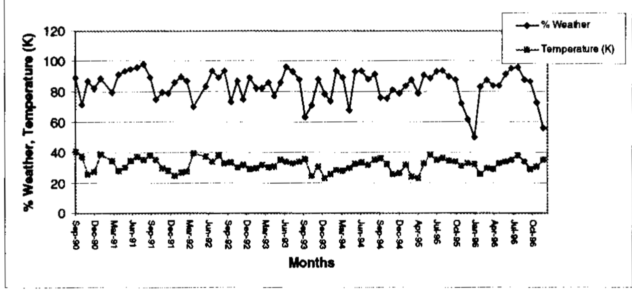


Figure 2. Optimum % Weather and Atmospheric Noise Temperature, Madrid, Sept. 90 to Dec. 96



While equations (1) through (6) provide a good measure for evaluating the effects of the weather on the data volume, one must take into account the fact that during adverse weather events there are times when the atmospheric noise temperature falls to an acceptable level. In these cases while a portion of the data may be recoverable, due to interdependency in the data, the recovered portion is useless and is counted as lost. In order to take into account such cases in the analysis of the WVR data, it is possible to calculate good periods and bad periods for a given T_{atm} threshold. In this analysis it is assumed that a good period occurs when five consecutive values of T_{atm} are below the threshold. A bad period occurs at any time the T_{atm} goes above the threshold.

Using this requirement another measure of data return volume could be obtained. For a given time period let $t_{good}(T_d)$ and $t_{bad}(T_d)$ be the total time duration of the good periods and total time duration of bad periods for design temperature T_d, respectively. To calculate these two values, let $\Omega(T_d)$ be the set of all indices n such that the temperature measurement T_n belongs to a bad period. Then

$$t_{good}(T_d) = \sum_n t_n \cdot I[n \notin \Omega(T_d)] \qquad (7)$$

and

$$t_{bad}(T_d) = \sum_n t_n \cdot I[n \in \Omega(T_d)] \qquad (8)$$

where I (x) is the indicator function and t_n is the period for which the nth temperature measurement is applicable.

Under these assumptions, for a given temperature threshold, T_d, the total data return volume is given by:

$$V_p(T_d) = \frac{t_{good}(T_d)}{t_{good}(T_d) + t_{bad}(T_d)} \cdot \frac{100 \cdot L(T_d)}{25 + T_d} \qquad (9)$$

Figure 3. Aggregate Monthly Optimum % Weather and Atmospheric Temperature, Madrid, Sept. 90 to Dec. 96

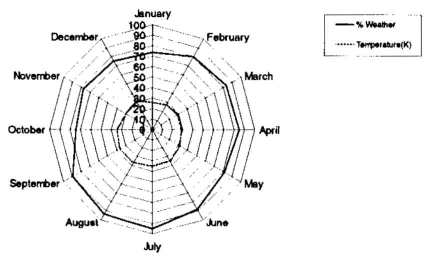
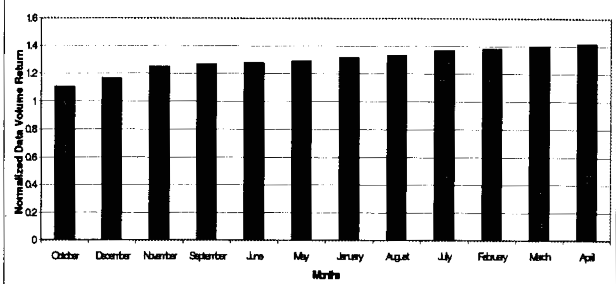


Figure 4. Ordering of the Month according to Data Volume Return



For the analysis in this paper the following measures are evaluated for each month: T_{opt}, V_{max}, $F_{atm}(T_{opt})$, V_g, $V_d(T_{opt})$, $V_p(T_{opt})$, and $V_p(\overline{T}_{opt})$, $V_p(T_{opt}^{(tot)})$, $V_p(T_{opt}^{(x)})$. $\overline{T}_{opt}$ is the average of T_{opt}'s over all 74 months, $T_{opt}^{(tot)}$ is the optimal temperature evaluated over all 74 months and $T_{opt}^{(x)}$ is the aggregate optimum temperature for month x (*e.g.*, $T_{opt}^{(May)}$ is the optimum temperature evaluated over all the data for the months of May).

IV. Statistical Results

The results of the analysis of the WVR data are summarized in Figures 1 through 8. Figure 1 indicates the statistical nature of the temperature measurements for each month. As seen from this figure, while the 99% T_{atm} measurements vary widely, the 80% T_{atm} measurements are rather well behaved. Almost all values of 80% T_{atm} are less than 40K and with two exceptions (January and December1996) all of them are less than 65K. Also notable is that some of the lowest 80% T_{atm} values occur for months of December through April (January and December 1996, December 1995 and April 1992 are the exceptions) which also have some of the highest 99% T_{atm} values. This indicates that while these months experience some severely adverse weather periods, during calm weather periods, these months tend to be dryer than other months. Since the data volume is inversely proportional to the T_{sys}, it is expected that in these months, during the calm weather periods the data rates could be increased due to lower T_{atm} values, thus compensating for the data losses that occur during adverse weather periods.

Figure 2 presents T_{opt}, and $F_{atm}(T_{opt})$ (expressed in terms of percentage weather). Note that while $F_{atm}(T_{opt})$ tends to vary from month to month (from 52% weather to 98% weather), T_{opt} is between 30K and 40K for most of the months. This indicates that the link could be designed by considering only one T_{sys} that would give approximately maximum data return volume without regards to monthly weather variations.

Figure 3 shows the $T_{opt}^{(x)}$, the aggregate monthly optimum temperature and $F_{atm}(T_{opt}^{(x)})$. Again this figure indicates that $T_{opt}^{(x)}$ values are roughly between 30K and 40K regardless of optimum percentage weather. Using these values the normalized data return was calculated for each month. The results for these are shown in Figure 4. This figure indicates that, on the average, the least amount of data is returned during October and December. November, September, June and May roughly return the same data volume as do the months of January and August. July, February, March and April tend to return the most data volume. The explanation for this is found in Figures 5a and 5b. These figures indicate the mean and standard deviation of T_{opt} and optimum % weather associated with each month. As seen in these figures, the months that have higher data volume return are those which have low T_{opt} and high % weather. In addition, they also show very little variation in T_{opt} with the exception of April. This discrepancy is attributed to the fact that the data from April 1992 contained a 14-day gap that caused April 1992 to have an uncharacteristically high T_{opt}.

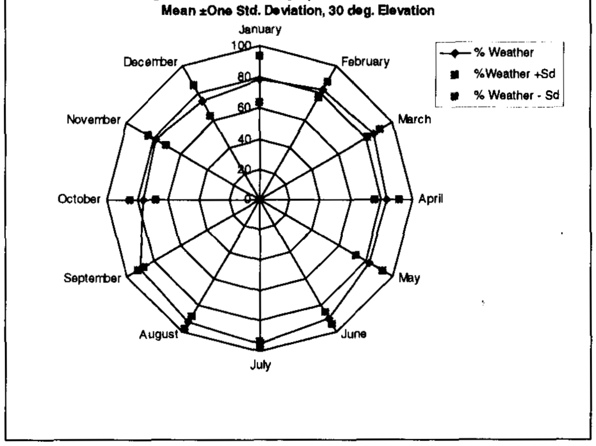


Figure 5a. Mean Monthly Optimum % Weather and Mean ±One Std. Deviation, 30 deg. Elevation

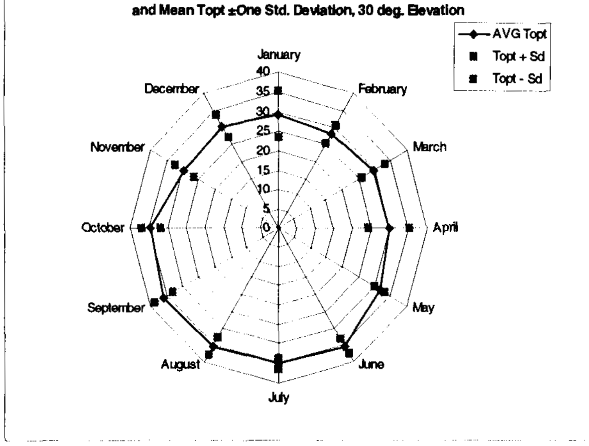


Figure 5b. Mean Monthly Optimum Topt and Mean Topt ±One Std. Deviation, 30 deg. Elevation

Figure 6 presents $V_d(T_{opt})$ (nominal data volume) and $V_{\max}$ (maximum effective data volume). Since $V_d(T_{opt})$ is a function of T_{opt} the variations seen in it are relatively minor from month to month. $V_d(T_{opt})$ tends to be between 1.0 and 1.5 and for most of the months it is approximately 1.2. On the other hand, $V_{\max}$ tends to vary much more from month to month,. This is due to the fact that while the value of T_{opt} does not vary much from month to month, those for $F_{atm}(T_{opt})$ do. As seen from this figure, with the exception of December and January '96 and December '95, the local minima usually occur in September and/or October (for the autumn months) and May and/or June (for the spring months). This is consistent with Figure 1.

Figure 7 provides a comparison between $V_{\max}$ and V_g. As seen from this figure even though $V_{\max}$ is lower than V_g, its value generally parallels that of V_g. In terms of total data volume over the 74 months $V_{\max}$ is approximately 74% of V_g. On a month to month basis $V_{\max}$ is between 55% (January '96) and 89% (August '91) of V_g.

Figure 8 shows the values of V_g (genie data volume), $V_{\max}$ (maximum effective data volume), $V_p(T_{opt})$ (actual data volume @ % weather), $V_p(\overline{T}_{opt})$ (actual data volume @ AVG Topt), $V_p(T_{opt}^{(tot)})$ (actual data volume at TOT Topt) and $V_p(T_{opt}^{(x)})$ (actual data volume @ MAVG Topt) over the 74 months. In terms of total data volume over 74 months, $V_p(T_{opt})$ is approximately 95.4% of $V_{\max}$ or 70% of V_g.

The value of $\overline{T}_{opt}$ for the 74 months is 32K. $T_{opt}^{(tot)}$ is 34K and corresponds to 84% weather for the whole data set. As seen from Figure 8, in general, $V_p(\overline{T}_{opt})$, $V_p(T_{opt}^{(tot)})$ and $V_p(T_{opt}^{(x)})$ follow $V_p(T_{opt})$ rather closely. This is due to the fact that for most months the values of $\overline{T}_{opt}$, $T_{opt}^{(tot)}$ and $T_{opt}^{(x)}$ are very close to that of T_{opt}. For those cases that there is a large discrepancy between $V_p(T_{opt})$ and $V_p(\overline{T}_{opt})$ the value of T_{opt} is not close to that of $\overline{T}_{opt}$. In terms of total data volume, $V_p(\overline{T}_{opt})$ is 94% of $V_p(T_{opt})$ or 66% of V_g over the 74 months. This indicates that designing for an average temperature causes on the average a data volume loss of only 4%. Similarly, if $T_{opt}^{(tot)}$ is used, over the 74 months $V_p(T_{opt}^{(tot)})$ is 96% of $V_p(T_{opt})$ and 68% of $V_p(T_{opt})$. If the monthly variations are taken into account for the link design by using $T_{opt}^{(x)}$ then over the 74-month period $V_p(T_{opt}^{(x)})$ provides 98% of $V_p(T_{opt})$ and 69% of V_g. This indicates that by using aggregate monthly temperatures for each month over the long run the link will perform nearly optimally.

Figure 6. Nominal Data Volume Return and Effective Data Volume Return per Month @ Optimum % Weather, Madrid, Sept. 90 to Dec. 96

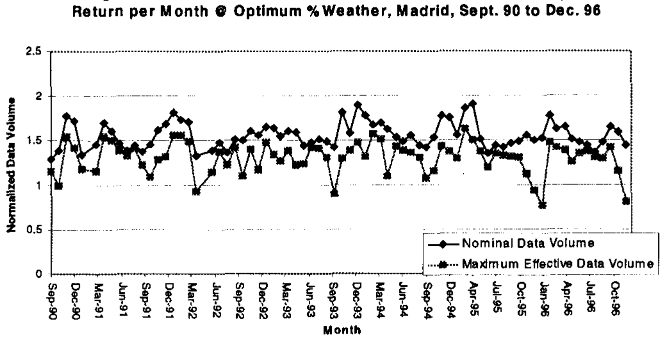
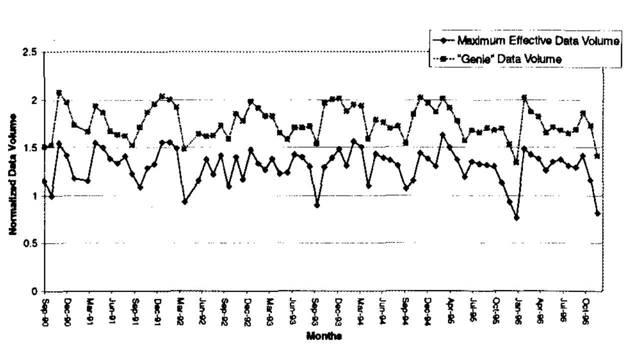


Figure 7.Genie Data Volume and Maximum Effective Data Volume, Madrid, Sept. 90 to Dec. 96

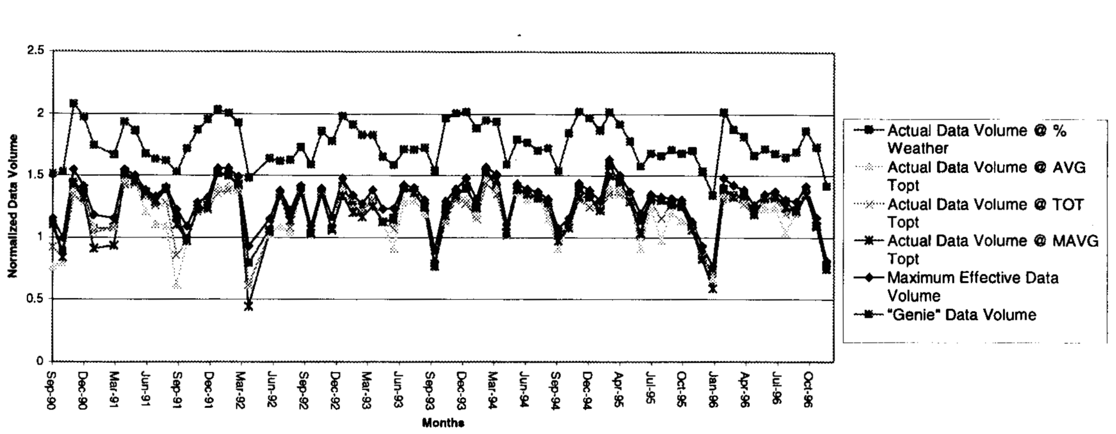


While using a fixed temperature from month to month seems to give near optimum performance, it must be remembered that even with a month to month optimization, the data return is still 30% below the upper bound on the data return. Since this upper bound was obtained by assuming perfect knowledge of the weather, it follows that any attempt to recover any of this 30% would involve weather prediction.

V. Ka-band Link Advanatage over X-band at Madrid DSCC for 34m BWG Antenna

Using the optimum atmospheric noise temperature for the whole data set ($T_{opt}^{(tot)}$ =34K) obtained in the previous section, the performance advantage of the Ka-band link over X-band (8.4 GHz) for a 34m beam waveguide (BWG) antenna is calculated. Assuming that the same effective isotropic radiated power (EIRP) is available at the spacecraft and the same modulation index and ground receiver losses are applicable for both frequencies, the Ka-band link advantage over X-band is shown in Table 1. These numbers are obtained from [4] and [5]. These documents include the latest measurements of the antenna gains and ground equipment noise temperature for X and Ka bands for 34m BWG antennas. Note that these numbers are for 30 degrees elevation, single frequency (antenna is configured to receive a signal frequency downlink, either X-band or Ka-band), nondiplexed (i.e., the antenna is not configured to transmit uplink). In the diplexed (i.e., antenna is configured to transmit uplink) or the dual frequency mode (i.e., antenna is

Figure 8. Genie Data Volume and Maximum Effective Data Volume, Madrid, Sept. 90 to Dec. 96



configured to support both X-band and Ka-band) the Ka-band advantage is greater by as much as 1 dB.

In addition, at higher elevations the advantage would be greater. Furthermore, it must be noted that spacecraft Ka-band amplifiers are not as efficient as X-band amplifiers. This fact must be taken into account in the selection of spacecraft downlink frequency. Note that the higher output RF power (>10W) Ka-band amplifiers are closer in efficiency to X-band amplifiers of similar power. Therefore, the gain presented in Table 1 should be interpreted as how much additional data Ka-band provides over the X-band for the same amount of DC power on the spacecraft as opposed to how much the spacecraft onboard power could be reduced at Ka-band to obtain the same amount of data as X-band.

Table1. Ka-band Advantage over X-band at 30 deg. Elevation, 34m BWG Single Frequency, Nondiplexed.

	Ka-band	**X-band**	**Ka-band over X-band Advantage (dB)**
Antenna Gain(dB)	78.88	68.37	10.51
System Noise Temp.(K) (T_{atm} + Other Noise)	34+27.51	7.5+21.89	-3.20
% Weather	84	90	-0.30
Atm. Loss	-0.57	-0.12	-0.45
		Total Gain (dB)	**6.56**

VI. Conclusions

WVR measurements for 74 months at DSCC-60 (Madrid) were used to estimate the total data return at Ka-Band. It was observed that by selecting an optimum value for the atmospheric noise temperature for the link design for each month the data return volume is approximately 74% of maximum total data return volume possible. If the interdependency of the data is taken into account then the average data return would fall to 70% percent of the upper bound. If aggregate optimum atmospheric noise temperature for whole data set is used the data return would be 66% percent of the upper bound on the maximum data return. If the monthly aggregate optimum atmospheric noise temperature is used the data return would be 69% percent of the upper bound. Finally, using the optimum atmospheric noise temperature for the whole data set it was shown that for the same radiated power at 30 degrees elevation the Ka-band link returns 6.56 dB more data than X-band.

Acknowledgment

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